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INVESTIGATING SCALING LIMITS OF A FIBER BASED RESONANT PROBE FOR METROLOGY APPLICATIONS

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INTRODUCTION

Currently, Inertial Confinement Fusion (ICF) and High Energy Density Science (HEDS) targets comprise components with dimensions in the millimeter range, while having micrometer-scale, high aspect ratio functional features, including fill-tube holes and counterbores, slotted patterns, and step-joint geometry on hemispherical targets. Representative geometry is shown in Figure 1. Future target designs will likely have additional challenging features. The dimensional metrology of these features is important for a number of reasons, including quantifying geometrical tolerances of as-built components prior to delivery, qualification of sub-components prior to assembly, and as a feedback mechanism for fabrication process development. Variations in geometry from part to part can lead to functional limitations, such as limited flow rates during target filling, unpredictable instabilities during an experiment, and the inability to assemble a target from poorly matched sub-components. Adding to the complexity are the large number and variety of materials, components, and shapes that render any single metrology technique difficult to use with low uncertainty.

Adapting standing wave probe technology [i] for micrometer sized features requires the understanding of the physical interaction between the oscillating, slender rod (probe) and the sample as a means of transferring information about the surface, such as topography and material properties, analogous to tapping mode atomic force microscopy (AFM) and/or instrumented indentation machines. By utilizing the variation in dynamic response of the probe as the tip interacts with a surface, information about the sample may be obtained and used for mapping surface topography, and potentially characterizing material properties. The novel long aspect ratio geometry of the probe enables the characterization of features such as small holes, slots, and corners, which typically cannot be accessed using AFM and instrumented indentation technology.

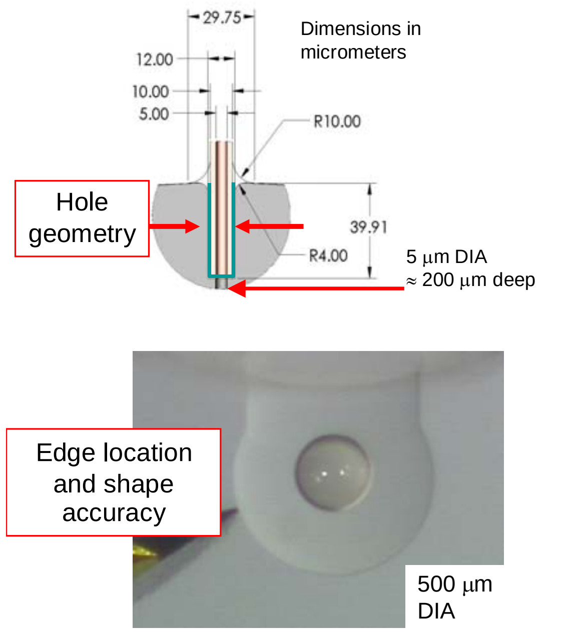

FIGURE 1. a) Fill tube assembly for NIC target designs. High aspect ratio, micrometer sized holes required for assembly. b) HEDS capsule assembly of silica bead molded in aerogel (50 mg/cc SiO_2). Target geometry requires micrometer concentricity and low density materials are difficult to profile without fracture.

Uncertainty of the surface location is a combination of near surface effects such as van der Waals and electrostatic forces combined with contact force such adhesion and meniscus contributions. In addition, environmental effects, such as thermal gradients and air turbulence, will influence probe performance and repeatability. A combination of complex nonlinear models of the tuning fork driver/sensor mechanics, fiber dynamics, circuit response and contact interactions have been developed for the current scale system in an effort to predict scaling limitations of this technology for characterizing micrometer sized features with nanometer sensitivity.

THEORY

To address the potential application of this technology for use on micrometer-scale, high aspect ratio features, a detailed understanding of the probe dynamics coupled with the nonlinear contact interactions is required. A set of complex numerical models have been derived to incorporate the drive/sensor piezoelectric effect, [ii,iii] dynamics of the probe fiber and surface interactions between the probe tip and surface. Modeling of the complete system has been a combination of finite element analysis and numerical integration to account for the complex nonlinear surface contact effects. This system has been broken down into four subsystems including the piezoelectric tuning fork driver/sensor, electronic sensing/drive circuits, beam dynamics and surface force interactions. Nonlinearities of the system are primarily dictated by the surface interaction of the probe tip as it comes into contact with the workpiece. Integrated within the model boundary conditions at the probe are elastic and inelastic impact [iv,v], meniscus, air damping, electrostatic, and Van der Waals and adhesion forces [vi,vii].

Because of the complexity of the dynamic interaction between the oscillating fiber (probe) and the surface, the system was modeled numerically in FORTRAN using Euler –Bernoulli beams for the fiber, piezoelectric beams for the tuning fork tines. Included in the numerical model are the drive electronics and the nonlinear boundary conditions. A schematic illustration of the model is shown in Figure 2. In addition, COMSOL multiphysics finite element analysis (FEA) package was used to verify modes and sensitivity of the tuning fork.

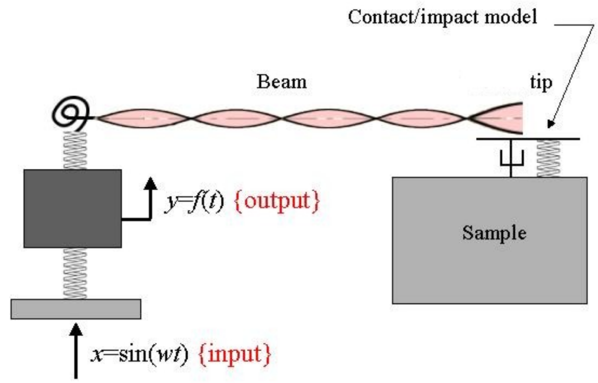

FIGURE 2. Schematic illustration of the numerical model derived representing the probe system dynamics and contact with a surface.

To verify that the model represents our system, the first task was to compare the frequency response of the model in the free-state (i.e. noncontact) with the experimental data, results of which are shown in Figure 3. In this case, material properties, geometry and electronics parameters are quantitatively measured and included in the calculation. However, damping of both the material and viscous effects of operating in air are "tuned" to properly represent probe dynamics in an air environment.

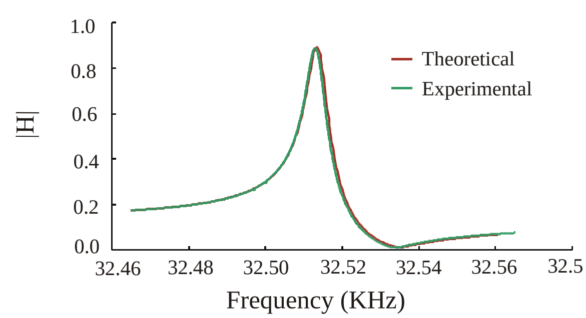

FIGURE 3. Theoretical and experimental frequency response of the probe system.

To validate the sensitivity of the tuning fork to applied voltage a nanoindentor was used to simultaneously measure load and displacement, see Figure 4. The results were compared to the COMSOL FEA model with an agreement of better than 10% and a strain sensitivity of 0.3 $nm \cdot V^{-1}$.

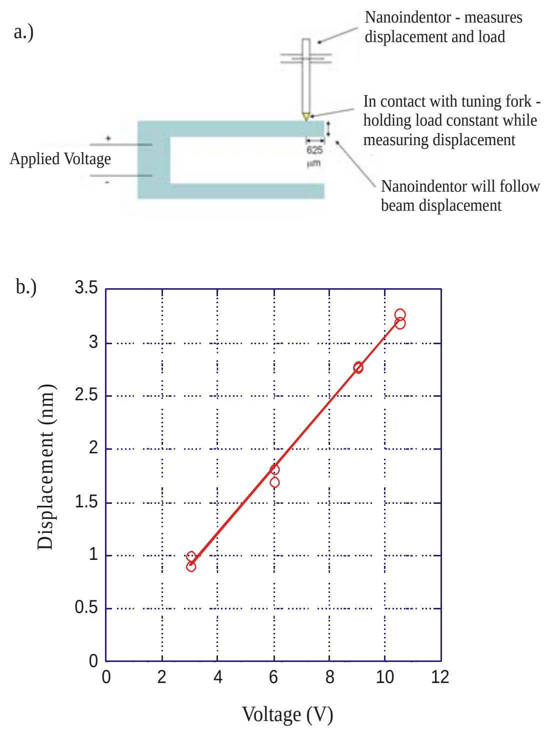

FIGURE 4. a.) Schematic representation of the nanoindentor test set-up. b.) Displacement as a function of applied voltage.

With the static and dynamic data well represented by the numerical model, the nonlinear boundary conditions of the probe tip contacting a surface were added. These include surface force effects, as mentioned earlier and an elastic and/or inelastic contact model. In general, the surface forces are dominated by meniscus effects at this probe scale. Figure 5b shows the complete model output as the probe tip comes into contact with a surface. Figure 5a are snap-shots in time of the mode shape of the beam and tuning fork as the surface is brought into contact. It is clear that energy imparted to the probe during initial contact excites lower order modes, however the amplitude only reaches ~40 μm with a ± 10 μm initial oscillation amplitude This effect can be observed experimentally and has proven to damp out due partially to air drag damping. The low mode oscillations tend to decrease in amplitude as the surface is continually stepped into contact as can be seen in the step #3 (0.72 μm) mode shape. Figure 5b is the RMS signal amplitude variation as the probe is stepped into contact with a surface as predicted by the model.

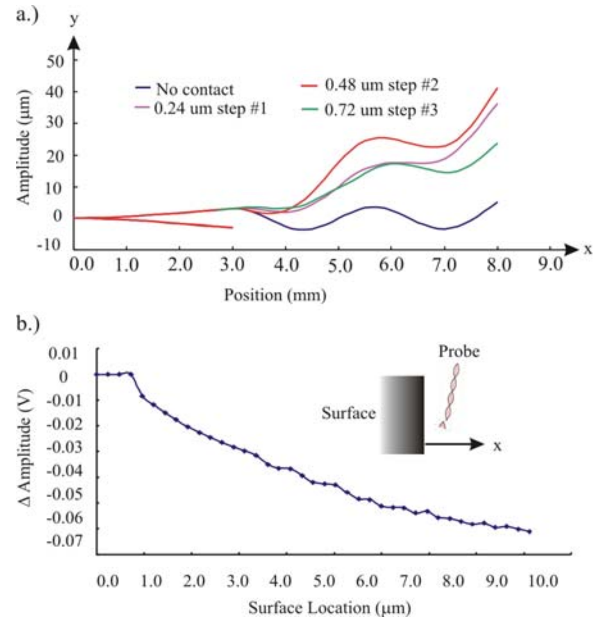

FIGURE 5. a.) Mode shape of probe as the surface is brought into contact with the probe tip. b.) Model predicted amplitude variation as the surface is brought into contact with the surface.

In general, the combination of the numerical model and the COMSOL FEA model predict the response of the system to better than 10% for the "free" and static cases. Introducing the nonlinear boundary conditions add uncertainty to model in that quantification of the relative surface force and material contributions is a bounded estimate. Surface forces were quantified experimentally using an atomic force microscope (AFM) by attaching a probe fiber tip to an AFM cantilever and measuring the forces of materials of interest, such as steel gage block and a gold foil. It has been found both analytically and experimentally that for a nominally 5.0 mm long fiber an adhesion force of ~ 100 μN will stick the fiber to the surface. Both the theoretical and measured surface forces for this scale system are ~ 10 μN, an order of magnitude smaller than the restoring force in the prestrained fiber allowing the probe tip to disengage from the surface.

Scaling the standing wave probe an order of magnitude, as illustrated in Figure 6 and using a similar analysis, the restoring force in the prestrained fiber is ~ 2 μN, while the adhesion force can be as much as 0.5 μN. In this case the nonlinear adhesion force is substantially more comparable to the restoring force at this scale. However, by either increasing the drive frequency and subsequently the strain energy in the fiber, and/or shortening the fiber length, more restoring force can be derived mediating the additional influence of the surface forces. An approximately 0.1 scale probe system has been designed and is currently being fabricated. The system will incorporate a ~400 kHz tuning fork driver/sensor and a Si etched fiber for the probe operating in nominally the 4th resonant mode.

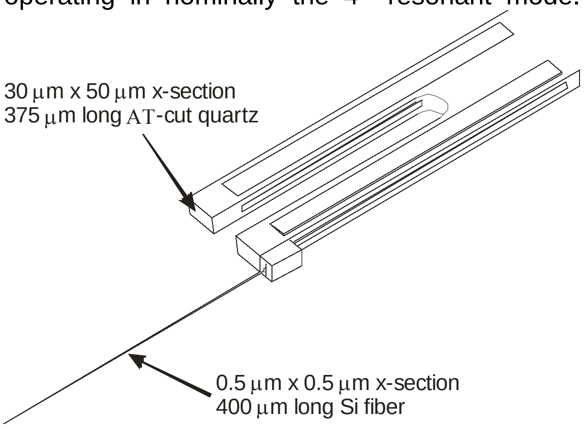

FIGURE 6. Scaled probe system design incorporating a ~0.1 scale AT- cut quartz tuning fork driver/sensor and a 0.5 μm × 0.5 μm x-section 400 μm long fiber.

CONCLUSIONS

A combination of numerical modeling, finite element analysis and experimental results developed for standing wave probes at the tens of micrometer scale has been derived and used to design a scaled version of the probe system. By increasing the frequency and/or mode of the oscillating fiber, adhesion forces at the probe/surface interface can be overcome even though they are more dominant at the smaller scale. A prototype scaled probe is currently being fabricated using microfabrication techniques commonly used for MEMS devices.

ACKKNWOLEDGEMENTS

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